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Charge Order and Superconductivity in a High-temperature Superconductor

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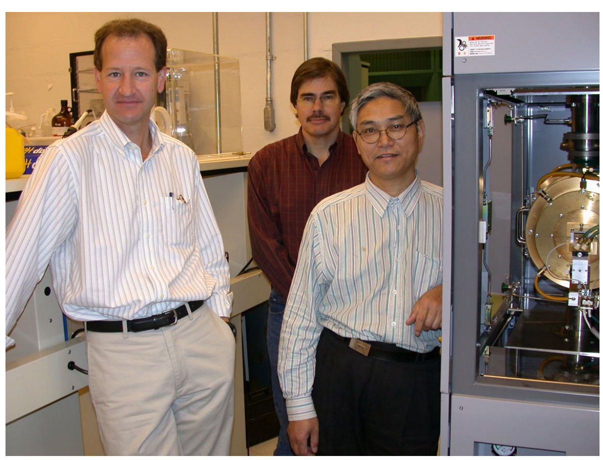
Superconductivity at elevated temperature was originally discovered in the lanthanum barium copper oxide materials ($La_{2-x}Ba_xCuO_4$, or LBCO). However, because these materials were difficult to grow as single crystals, work quickly shifted to the analogous $La_{2-x}Sr_xCuO_4$ (LSCO) materials. Recently, large single crystals of LBCO have been grown that are suitable for optical studies. All high-temperature superconductors share the trait that the parent compounds are insulating, and that superconductivity is induced by chemical doping to produce a superconducting "dome"; LBCO is superconducting for Ba-dopings of about 0.05 to 0.23. Curiously, at the 1/8 doping, charge-order develops and superconductivity is destroyed, leading to an unusual electronic state.

In most cases, superconductivity develops from a metallic state, and is characterized by the formation of a superconducting energy gap at the Fermi surface. In metals and alloys, this gap is isotropic. However, a unique feature of the copper-oxide superconductors is that the gap is highly anisotropic, actually going to zero at some points on the Fermi surface (this is referred to as a *d*-wave gap). Optical studies allow the nature of both the metallic and superconducting states to be probed.

Single crystals of LBCO have been cleaved in air, revealing large, optically flat surfaces oriented parallel to the copper-oxygen planes where the superconductivity is thought to originate in these materials (**Figure 1**). The temperature dependence of the reflectance has been measured at a near-normal angle of incidence over a wide frequency range (about 2 meV to over 4 eV). The reflectance is in fact a complex quantity, consisting of an amplitude and a phase; in this case, only the amplitude is measured. However, if the reflectance is measured over a wide enough range (as is the case here), then the Kramers-Kronig relations may be used to determine the phase – once these two quantities are known, other quantities such as the optical conductivity may be calculated. The optical conductivity of LBCO at the 1/8 doping is shown in **Figure 2**. The conductivity of metals is often described by the simple Drude model, which may be described by a plasma frequency (a measure of the concentration of free carriers), and a scattering rate; the frequency response is a Lorentzian centered at the origin, and the width at half maximum is the scattering rate. This simple picture describes the optical conductivity of LBCO quite well, at least until about 60 K. However, for this particular doping LBCO undergoes an orthorhombic to tetragonal transition at about 60 K, leading to formation of static charge stripes. Long-range charge order in a material often leads to the formation of a charge gap that destroys the conductivity in the material. However, as **Figure 2** clearly shows, while the response associated with the Drude component is shrinking, the conductivity remains metallic down to the lowest measured temperature. We interpret this response to indicate that the charge order is responsible for a partial gapping of the Fermi surface. Angle resolved photoemission studies on this



Authors (From left to right): Christopher Homes, John Tranquada, and Genda Gu standing beside an optical furnace in which the LBCO samples were grown.

material do indeed detect a gap in this material below 60 K, but the gap is highly anisotropic and has a *d*-wave character; the metallic excitations are associated with the ungapped or nodal regions. This behavior is also observed in the normal-state of the underdoped copper-oxide materials, which are referred to as "nodal metals". It is tempting to associate this gap with a competing instability, such as a charge density wave. However, the fact that the superconductivity recovers quickly to on either side of the 1/8 anomaly suggests that the gap we observe in the 1/8 material is in fact the superconducting gap, but with a near total absence of phase coherence.

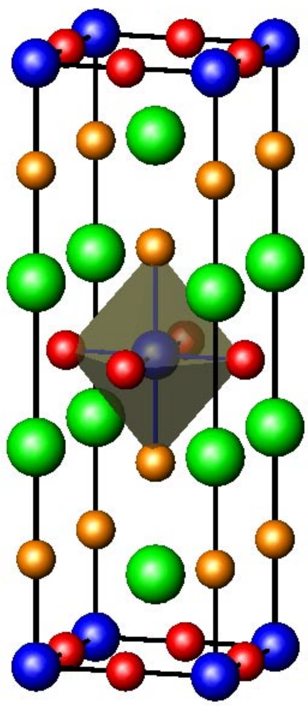


Figure 1*: The unit cell of (La,Ba)$_2$CuO$_4$ [La, (Ba) – green, Cu – blue, O – red (sheet), orange (apical)] illustrating the copper-oxygen (ab) planes and bond coordination; the long axis is the c axis.*

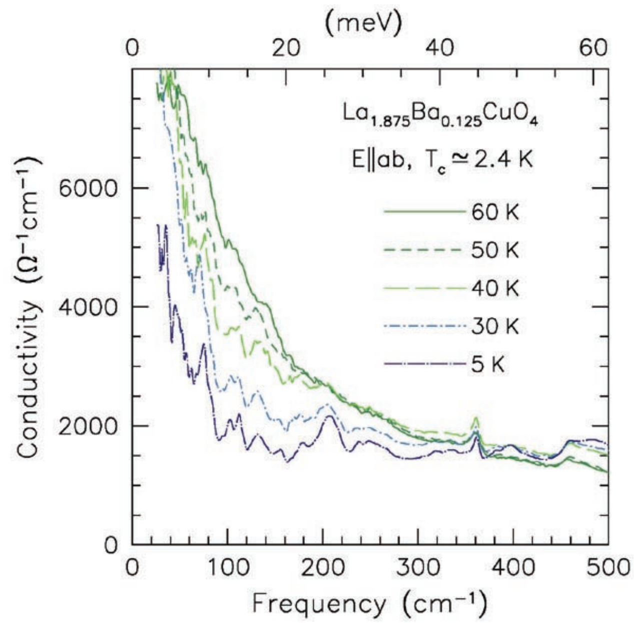


Figure 2*: The ab-plane optical conductivity of LBCO for the 1/8 doping in the infrared region between 60 and about 5 K, showing a steady decrease and narrowing of the Drude-like component.*